

SPACE TECHNOLOGY LABORATORIES, INC.

FACILITY FORM 602

N65-87670

(ACCESSION NUMBER)

25 (PAGES)

(THRU)

None (CODE)

(NASA CR OR TRN CR AD NUMBER)

(CATEGORY)

ESTIMATE OF SPACE RADIATION EFFECTS ON  
SATELLITE SOLAR CELL POWER SUPPLIES

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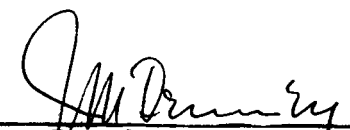
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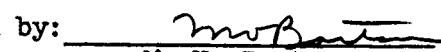
20 October 1961

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ABSTRACT

The charged particle intensity and energy distribution at the heart of the inner and outer Van Allen belts is compared with the experimentally determined radiation sensitivity of silicon solar cells. Energy dependence of the radiation damage and solar cell characteristics is included in the lifetime estimate of spacecraft solar cells. Use of charged particle range energy relations and the differential intensity of the Van Allen radiation results in an estimated effectiveness of thin protective shields. Comparative advantages of thin shields, advanced cell designs, solar efficiency, and solar cell system over-design are discussed with respect to radiation resistance of spacecraft power supplies.

ACKNOWLEDGEMENT

We are grateful to a host of individuals for their assistance and encouragement. Professor R. Thornton and Mr. J. Vale, University of California, Lawrence Radiation Laboratory; Dr. S. C. Wright, Fermi Institute, University of Chicago; Professor J. Richardson, UCLA; Dr. B. Ross, Hoffman Semiconductor; Dr. M. Wolff, Heliotek; Dr. W. Brown and Mr. F. Smits, Bell Telephone Laboratories, deserve particular mention. Professor G. Pearson, Stanford University, has contributed valuable advice and criticism. Encouragement and support of the high energy proton experiments was provided by the National Aeronautics and Space Administration, Contract NAS 5-613.

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## I. INTRODUCTION

Bands of energetic charged particles near the earth were discovered in early satellite experiments. Additional spacecraft experiments, performed in the last few years, have identified the major features of the Van Allen belts and have provided evidence of the charged particle intensity associated with solar flares in regions beyond the bands of magnetically trapped particles. The hard radiation is probably one of the most severe aspects of the space environment for many spacecraft components. Solar cells, because of their sensitivity to radiation damage and widespread use in spacecraft, have been studied more extensively with regard to radiation damage than most spacecraft components. This paper summarizes the results of many of these studies and analyzes the protection provided by thin shields in order to obtain estimates of the rate of deterioration of silicon solar cells in earth orbits.

The flux and energy of charged particles in the Van Allen bands have been measured at many altitudes and latitudes. In general, two Van Allen belts are observed, both centered about the geomagnetic equator. The inner belt contains protons and electrons and the outer belt contains electrons. We have taken the results of Naugle's<sup>1</sup> survey as the environmental basis for our calculations. Because protons dominate the inner belt, the inner belt electrons have been neglected. The proton intensity,  $\phi = 2 \times 10^4 \text{ p/cm}^2 \text{ - sec}$  for  $E > 40 \text{ Mev}$ , has been extrapolated to 5 Mev according to Naugle's energy dependence. We have arbitrarily terminated the proton spectrum at 5 Mev, in the absence of detailed information at low proton energies. The electron intensity,  $\phi = 1 \times 10^8 \text{ e/cm}^2 \text{ - sec}$  for  $E > 200 \text{ kev}$ , has been extrapolated according to Naugle's energy dependence. The low energy limit for electrons is not critical because this case becomes damage limited at 150 kev.

In order to avoid the problems of altitude and latitude dependence of the particle intensity and energy distribution, two cases have been considered: continuous exposure to the inner belt protons and continuous exposure to the outer belt electrons. These conditions are equivalent to circular orbits at the geomagnetic equator at altitudes of about 3600 km and 16,000 km, respectively. These orbits are the most severe with respect

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<sup>1</sup>J. E. Naugle, Nucleonics, Page 89, April, 1961

to radiation damage, and most satellites will experience only cyclic exposure to the charged particle belts because of their inclination and ellipticity. The lifetime estimates presented in this paper should be appropriately reduced for orbits in which the exposure is less severe.

## II. RADIATION EFFECTS IN SOLAR CELLS

The effect of charged particle radiation on semiconductor devices has received considerable attention in recent years. Of particular interest here are the effects of electrons and protons on solar cells. Recent experiments<sup>2</sup> demonstrate that energetic protons seriously degrade the electrical characteristics of solar cells. The degradation of current-voltage characteristics as a function of integrated 740 Mev proton flux is shown in Figure 1 for typical p on n gridded silicon solar cells. As is evident in the figure, the short circuit current typically degrades more rapidly than the open circuit voltage while the degradation in power output, although dependent on loading, closely follows the short circuit current degradation. The short circuit current degradation, Figure 2, is typical of commercial cells; the spread in degradation between cells with the same characteristics is less than 5 per cent. The dependence upon cell parameters is discussed later. After the knee of the curve has been exceeded, the short circuit current degradation depends upon the logarithm of the integrated flux. Use of different illumination spectra affects only the degradation rate, i.e., the slope of the curve; whereas, the linearity of the degradation with the logarithm of the integrated flux is independent of the illumination spectrum. In addition, measurements of pre and post-irradiation solar cell spectral response characteristics show that the long wavelength response of the cells is preferentially reduced. Similar relationships are obtained with electron irradiation. These data, i.e., logarithmic dependence of short circuit current degradation on integrated proton flux and rapid degradation of long wavelength spectral response, indicate that the primary effect of the radiation damage is the reduction of the minority carrier lifetime in the base, or parent, material of the solar cell. Present understanding of defect mechanisms in semiconductors implies that this reduction in minority carrier lifetime and corresponding diffusion length is primarily due to the introduction of recombination

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<sup>2</sup>J. M. Denney, R. G. Downing, STL Report 8987-0001-RU-000, 15 September 1961 (Final Report, NASA Contract NAS 5-613)

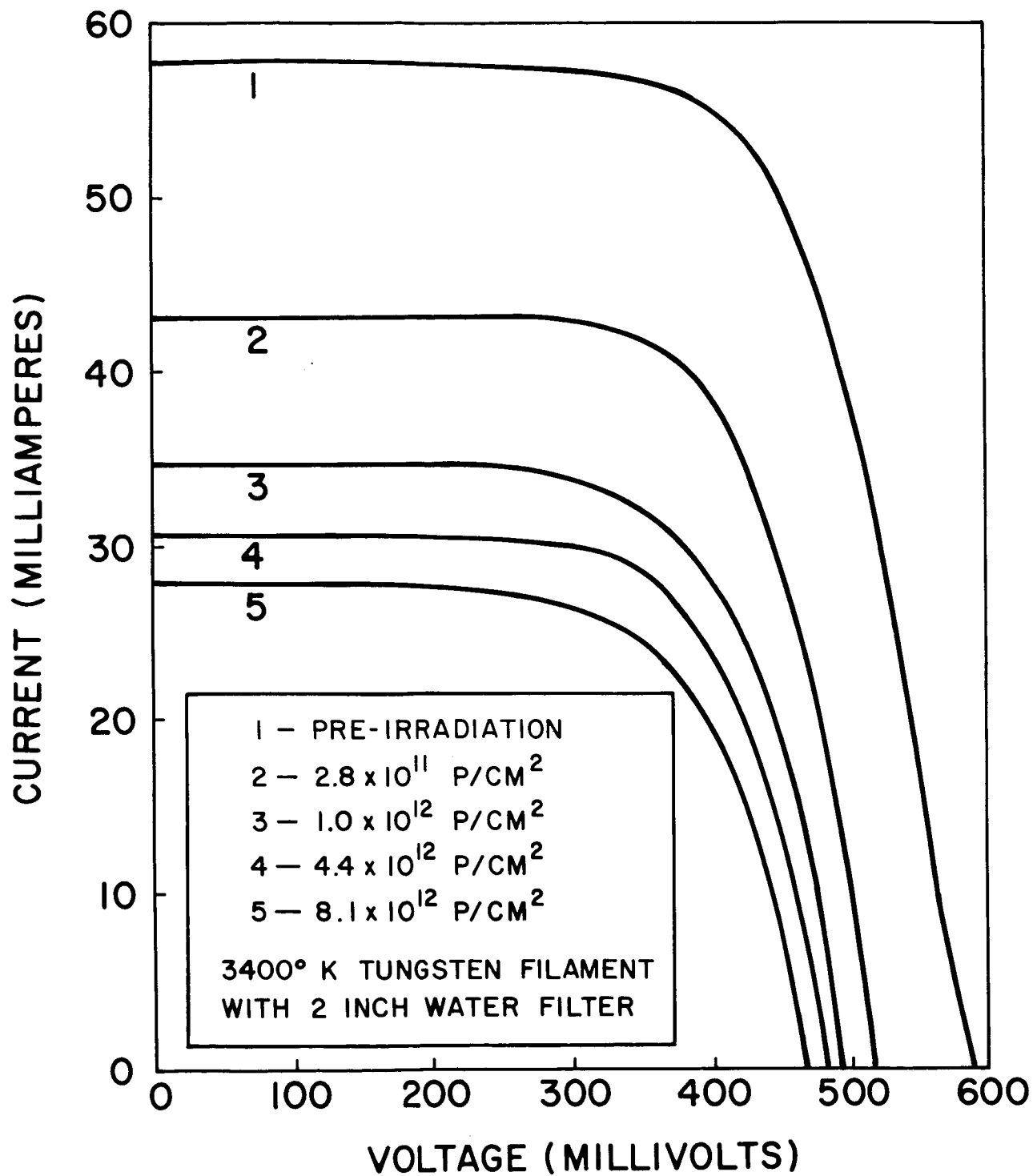


Figure 1. Typical p on n Gridded Silicon Solar Cell I-V Characteristic Degradation with 740 Mev Protons



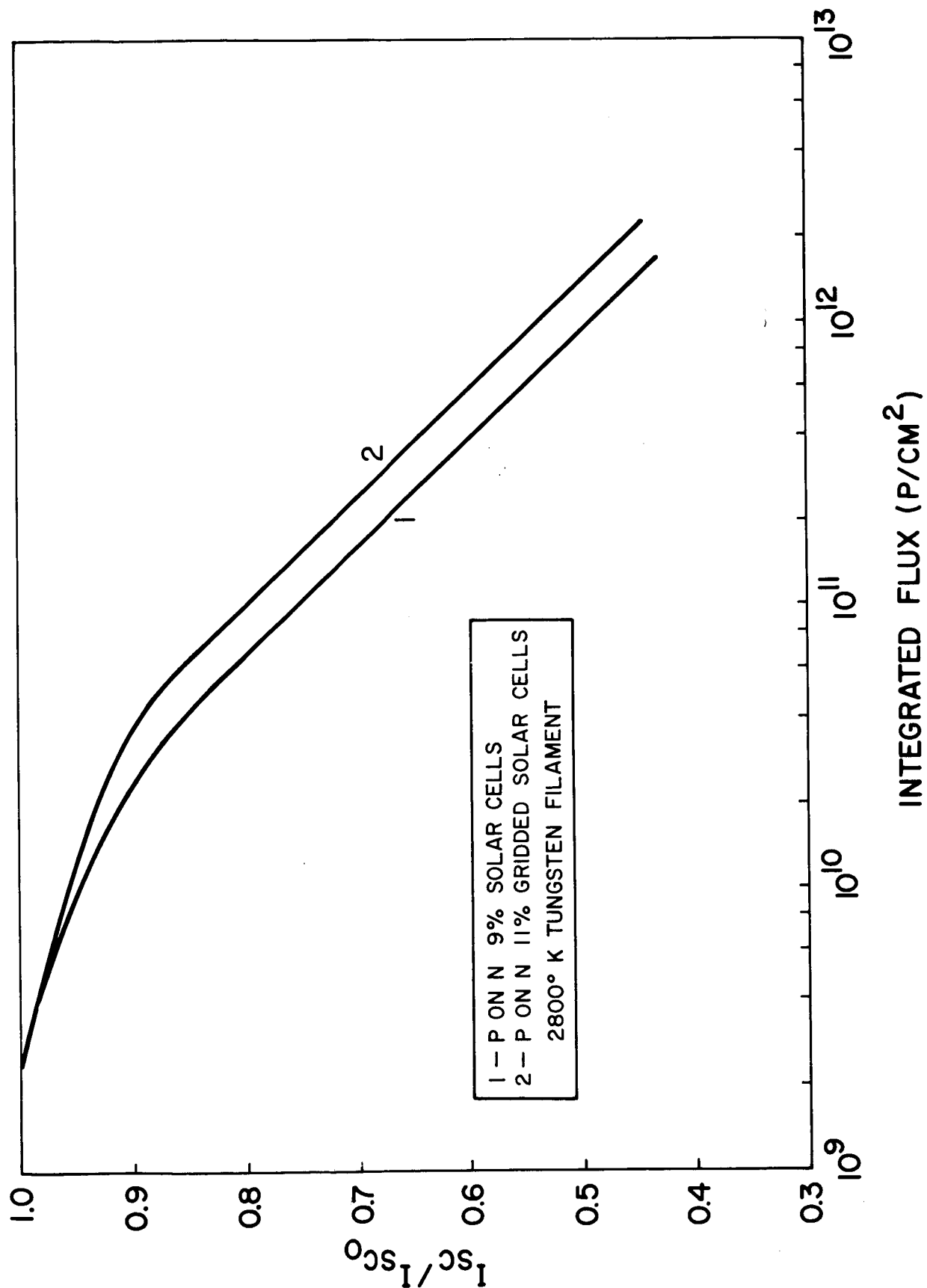


Figure 2. Typical p on n Silicon Solar Cell Short Circuit Current Degradation with 450 Mev Protons

centers by the point defects produced through scattering processes.

The short circuit current of a solar cell can be expressed as a function of incident energy spectrum, solid state device parameters, and optical dispersion characteristics through a complete solution of the diffusion equation with appropriate boundary conditions for each contributing region. If a 2800°K tungsten spectrum is used as a source, solar cell geometry (Figure 3) and the high infrared component of the source produce a short circuit current output which consists primarily of diffusion limited base current. For these conditions, a good approximation for short circuit current can be obtained by solution of the diffusion equation for the base region only, thus greatly simplifying the required assumptions and calculations. The resulting general solution for the short circuit current density produced in the base region by 2800°K tungsten illumination is

$$J = \frac{e \phi(\lambda)}{\alpha L^2 - 1} \left\{ \frac{\left[ \alpha L (\infty D - S) e^{-\frac{X}{L}} + S \cosh \frac{X}{L} + \frac{D}{L} \sinh \frac{X}{L} \right]}{\left[ S \sinh \frac{X}{L} + \frac{D}{L} \cosh \frac{X}{L} \right]} - \alpha L^2 \right\} \quad (1)$$

where  $e$  is electronic charge,  $\phi(\lambda)$  is 2800°K tungsten spectrum,  $\alpha$  is optical absorption coefficient,  $L$  is minority carrier diffusion length,  $D$  is diffusion constant,  $S$  is surface recombination velocity,  $X$  is width of base region, and  $\lambda$  is wavelength.

Since typical solar cells are made from parent material of the order of 0.015 inch to 0.020 inch thick, and typical minority carrier diffusion lengths are of the order of 50 to 100 microns, the quantity  $X/L$  is of the order of 10. Equation (1) then reduces to

$$-J = e \phi(\lambda) \frac{\alpha L}{\alpha L + 1} \quad (2)$$

The optical absorption coefficient,  $\alpha$ , is a strong function of wavelength in the region of interest ( $\lambda = 0.4\mu$  to  $1.1\mu$ ). Equation (2) is expressed in integral form over the region of interest as

$$-J = e \int_{\lambda_1}^{\lambda_2} \phi(\lambda) \left[ \frac{\alpha(\lambda) L}{\alpha(\lambda) L + 1} \right] d\lambda \quad (3)$$

where the sign of  $J$  is indicative only of the direction of current flow.

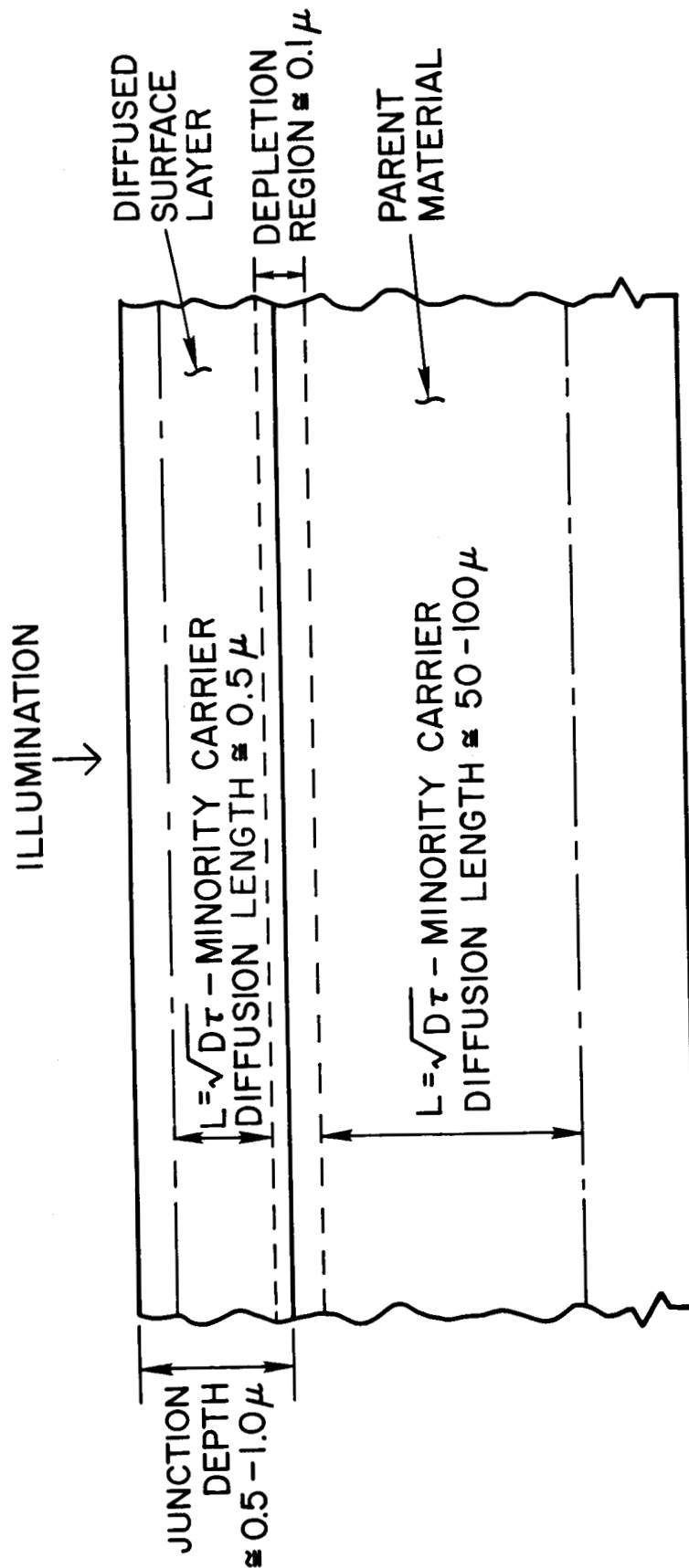


Figure 3. Diagram of Typical Solar Cell Geometry

If the function  $\alpha(\lambda)$  is explicitly expressed, Equation (3) can be integrated to yield the functional dependence of short circuit current density on minority carrier diffusion length for the given illumination spectrum. The function  $\alpha(\lambda)$ , however, is an experimentally determined function subject to the experimental inaccuracies normally associated with rapidly varying empirical functions of this type. An alternative solution, therefore, is the numerical integration of Equation (3) using published values of optical absorption coefficients<sup>3</sup> in place of an explicit function  $\alpha(\lambda)$ . The results of the numerical integration are summarized by an approximate relationship:

$$J \approx \log L \quad (4)$$

It is seen that, within the limits of the assumptions used for this particular case of interest, the short circuit current density is linearly proportional to the log of the minority carrier diffusion length. This result is entirely consistent with the observed behavior of solar cells under 740 Mev and 450 Mev proton bombardment as previously presented.

In order to obtain a more direct experimental verification of this relationship, a series of solar cells were subjected to 1 Mev electron bombardment in a Van de Graaff accelerator while simultaneous measurements of short circuit current and minority carrier diffusion lengths were obtained. The short circuit current was measured as a function of integrated flux by standard techniques using a 2800°K tungsten spectrum. The corresponding minority carrier diffusion lengths were determined through electron illumination with the accelerator. The results, e.g., Figure 4 for a typical p on n silicon solar cell, conclusively show that the relationship presented in Equation (4) is a valid first order approximation relating radiation damage to minority carrier diffusion length. The normalization constant for the curve  $\log L/\log L_0$  has been omitted for clarity since the importance of the data lie primarily in the comparison of slopes. The assumption used in the numerical integration that the function  $\alpha(\lambda)$  is independent of radiation damage appears valid for the range of defect densities encountered here.

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<sup>3</sup>R. Braunstein, A. R. Moore, and F. Herman, Physical Review, 109, 695, (1958)

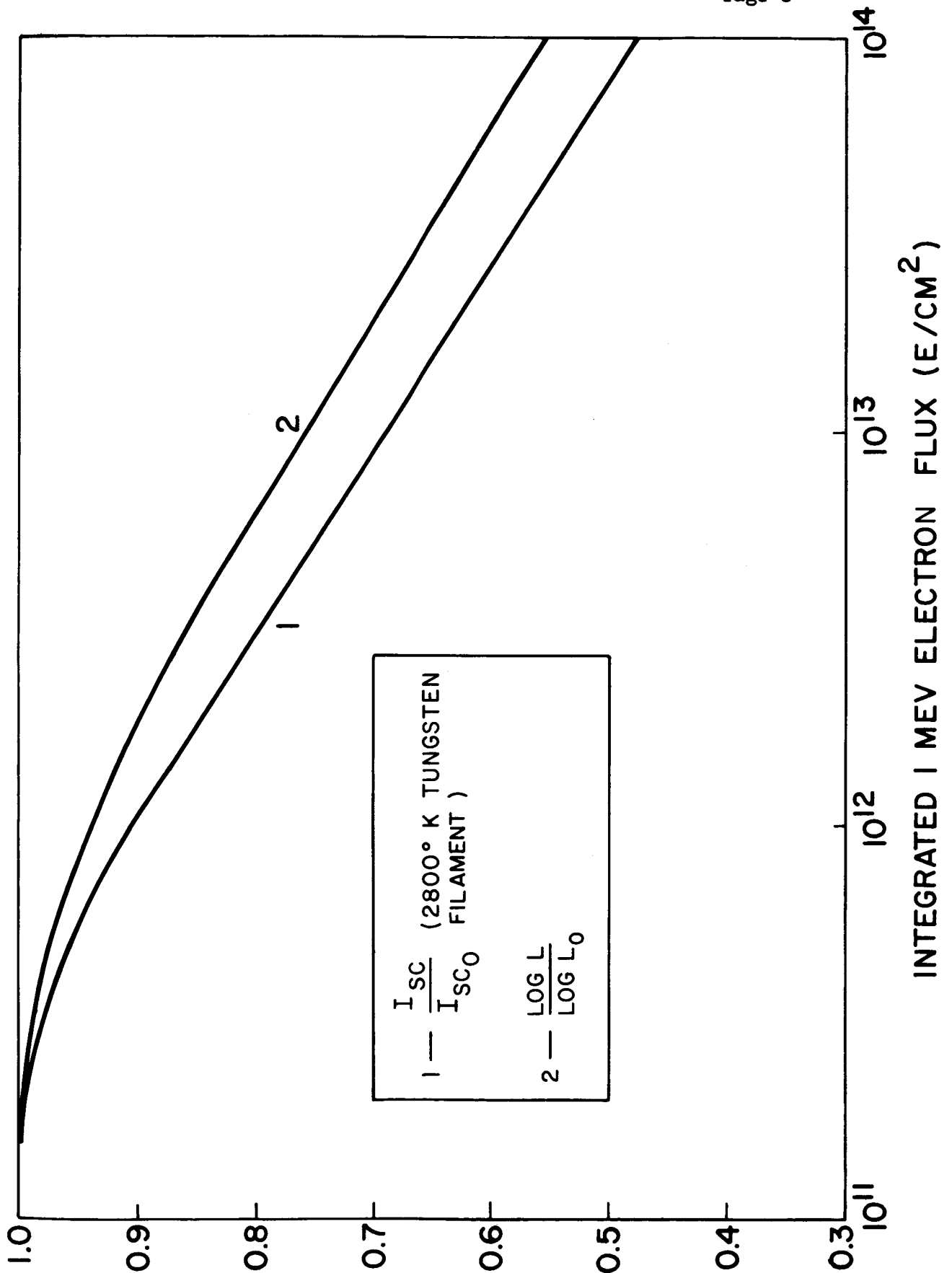


Figure 4. Comparison of Solar Cell Short Circuit Current and Minority Carrier Diffusion Length During Electron Bombardment

The use of 1 Mev electrons to produce radiation effects is convenient in that a homogeneous density of defects within the active volume of the solar cell is produced. For this case, it has been shown that application of simple displacement theory is relatively consistent with experimental results. For example, the reduction of minority carrier lifetime in semiconductor crystals through the action of defects as recombination centers under electron bombardment has been shown to follow the general relationship:

$$\frac{1}{\tau} \propto \frac{1}{\tau_0} + k \phi \quad (5)$$

where  $\tau$  is minority carrier lifetime and  $\phi$  is integrated electron flux. Examination of the data obtained for solar cells under electron bombardment (Figure 4) indicates a relationship of the form:

$$\frac{1}{L^2} = \frac{1}{L_0^2} + k \phi \quad (6)$$

which is consistent with the previously reported data.

In summary, the results of the theoretical analysis and the experimental observations are self-consistent. The evident conclusion, therefore, is that solar cell degradation during irradiation is primarily due to the reduction of minority carrier diffusion length through defect produced recombination centers.

### III. PRODUCTION OF POINT DEFECTS

Because point defects are initially produced by Rutherford scattering, the process is energy dependent. Also, since all of the experimental evidence considered here has been obtained at room temperature, the mobility of point defects implies that clustering or chemical trapping of the defects has occurred. For protons in the range 1 Mev up to at least 50 Mev, the experiments<sup>2</sup> have shown that the rate of defect production follows a modified Rutherford scattering equation:

$$\sum d \propto \frac{1}{E} \log \frac{T_m}{T_d} \quad (7)$$

where  $\sum d$  is the total displacement cross section including progeny defect production,  $E$  is the proton energy,  $T_m$  is the maximum knock-on energy,

and  $T_d$  is the displacement energy ( $Si = 12.5$  ev). The modification of the classical Rutherford equation which predicts a  $1/E$  energy dependence is necessary in order to account for the increased defect production by the knock-on atom; this defect production increases slowly with the incident proton energy.

Above about 50 Mev, an additional damage mechanism becomes effective. Experiments<sup>4</sup> have shown that the damage produced at 400 Mev to 740 Mev is considerably higher than predicted by Equation (7). This increased damage effectiveness of high energy protons is mainly due to inelastic nuclear reactions. Nuclear spallation is presumed to be the primary inelastic damage production mechanism. The model chosen to describe the spallation contribution to point defect formation can be described as follows: the energetic proton penetrating the silicon nucleus causes the prompt emission of a small number of protons and neutrons; the excited residual nucleus then emits additional delayed nucleons in returning to its ground state. The residual, recoil nucleus is scattered in the forward direction because of momentum transfer during the emission of the prompt prongs. A number of difficulties result from attempts to analyze this inelastic nuclear reaction. Estimates based on Monte Carlo calculations<sup>5</sup> lead to an equation of the type:

$$\bar{T}_{out} = T_{in} - E^* (n-1)B \quad (8)$$

Average values for the excitation energy ( $E^*$ ) and the number ( $n$ ) of prompt prongs can be inserted in Equation (8) in order to estimate the average kinetic energy ( $\bar{T}_{out}$ ) of the prompt prongs for a given incident proton energy ( $T_{in}$ ). ( $B$  is the average binding energy of a nucleon in the silicon nucleus:  $B \approx 8-9$  Mev.) Conservation of momentum among the incident proton, outgoing prongs, and the recoil nucleus gives an estimate of the energy of the recoil nucleus. This estimate indicates that the nuclear recoil is the most significant contributor to defect production. It should be recognized, however, that this model and analysis are quite crude. The results indicate that damage production at 400 Mev to 740 Mev is about 10 times larger than obtained from Rutherford scat-

<sup>4</sup>J. M. Denney, R. G. Downing, and A. Grenall, ARS Progress in Astronautics and Rocketry, 3, 363, (1961)

<sup>5</sup>N. Metropolis, R. Bivins, M. Storm, A. Turkevich, J. Miller, and G. Friedlander, Physical Review, 110, 185, (1958); *ibid.* Physical Review, 110, 204, (1958)

tering at these energies. One evidence of the inaccuracy of the spallation model is that it predicts increasing damage effectiveness with increasing energy in this range, whereas this energy dependence has not been observed.

In order to formulate the energy dependence of proton radiation damage, the analysis has been compromised in favor of the experimental results. Experiments<sup>2</sup> at 400 Mev to 740 Mev show a damage production rate which is independent of proton energy. On the other hand, at lower proton energies, experiments have shown that damage production rate follows the modified Rutherford equation. We have combined these two observations in Figure 5, drawing intersecting straight lines. The result indicates that the damage decreases with increasing proton energy up to 75 Mev and is independent of proton energy above 75 Mev. Figure 5 is well supported by experimental results at 20 Mev and below and in the range 400 Mev to 740 Mev. The exact energy dependence in the range 50 Mev to 300 Mev is extremely uncertain. Figure 5 is a crude approximation in this energy range.

Below about 1 Mev, radiation damage in solar cells becomes limited by the decreasing range of the proton. Radiation damage at very low proton energies has not been investigated; we have arbitrarily terminated the analysis at 1 Mev.

Electrons create point defects in silicon almost exclusively through the mechanism of relativistic Coulomb scattering; also, because of the large mass difference between the electron and silicon nucleus, an inefficient momentum transfer results. The energy required to displace the silicon atom has been found to be about 12.5 ev, which requires an incident electron of 145 kev or greater. The relativistic Rutherford equation describing the damage cross section for electrons which can produce silicon knock-ons above the displacement energy is

$$\sigma_d = \frac{\pi Z^2 e^4}{m^2 v^4 \gamma^2} \left[ \left( \frac{T_m}{T_d} - 1 \right) - \beta^2 \log \frac{T_m}{T_d} \right] \quad (9)$$

where  $\sigma_d$  is the atomic displacement cross section;  $Z$  is the atomic number (Si = 14);  $e$ ,  $m$ , and  $v$  are the electronic charge, mass, and velocity, respectively;  $\beta$  is  $v/c$  ( $c$  is the velocity of light);  $\gamma^2$  is  $1/1-\beta^2$ ;  $T_d$  is the displacement energy (Si = 12.5 ev); and  $T_m$  is the maximum knock-on



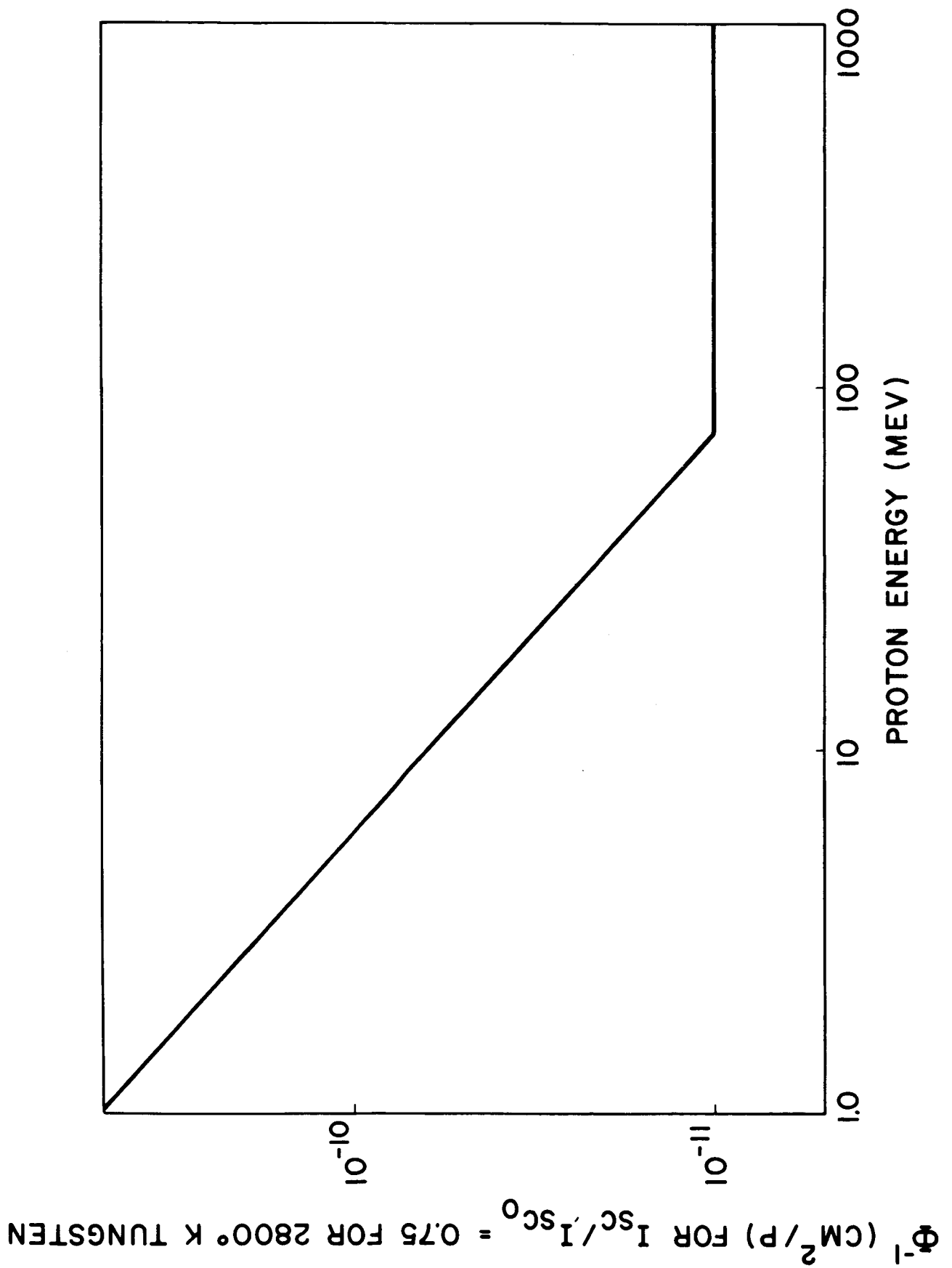


Figure 5. Energy Dependence of Silicon Solar Cell Short Circuit Current for Proton Bombardment

energy. (This equation is applicable to low atomic number elements; terms of the order of  $Z/137$  are neglected.)

Equation (9) has been shown<sup>6</sup> to describe the energy dependence of electron damage in silicon. Slight modification near the threshold is necessary because of the decrease in effective range of the electron. Figure 6 has been constructed using experimental results and the relativistic Rutherford energy dependence.

Figures 5 and 6 present the energy dependence of the radiation damage in terms of the integrated flux required to produce a 25 per cent decrease in short circuit current of a typical silicon solar cell. This has been done in order to avoid quantitative difficulties in relating defect densities to the change in short circuit current. The ordinate in both figures can be suitably modified for more radiation resistant cells or to yield defect density.

#### IV. EFFECT OF SHIELDING

The rate at which damage is produced in spacecraft solar cells can be determined as a function of the charged particle energy by multiplying the differential charged particle intensity by the energy dependent damage rate (Figures 5 and 6) and integrating over total energy distribution of the charged particles. Obviously, the particle intensity and energy distribution depends upon the spacecraft orbit. A multiplicity of results is possible. We have considered two cases: (1) continuous exposure at the heart of the inner belt and (2) continuous exposure at the heart of the outer belt. The flux and energy distribution of the charged particles in each region has been estimated by Naugle<sup>1</sup> based on a variety of satellite experiments. The results of our calculations depend directly upon the flux and energy distribution we have assumed; our results should be modified appropriately as additional information on the Van Allen belts becomes available. These calculations do not include the isotropic geometry correction or the effects of energy straggling in the shields.

The time to produce a 25 per cent change in output of a typical solar cell as a function of the integral proton spectrum in the heart of the inner belt is shown in Figure 7. The results shown in Figure 7

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<sup>6</sup>R. G. Downing, ARS Progress in Astronautics and Rocketry, 3, 325, (1961)

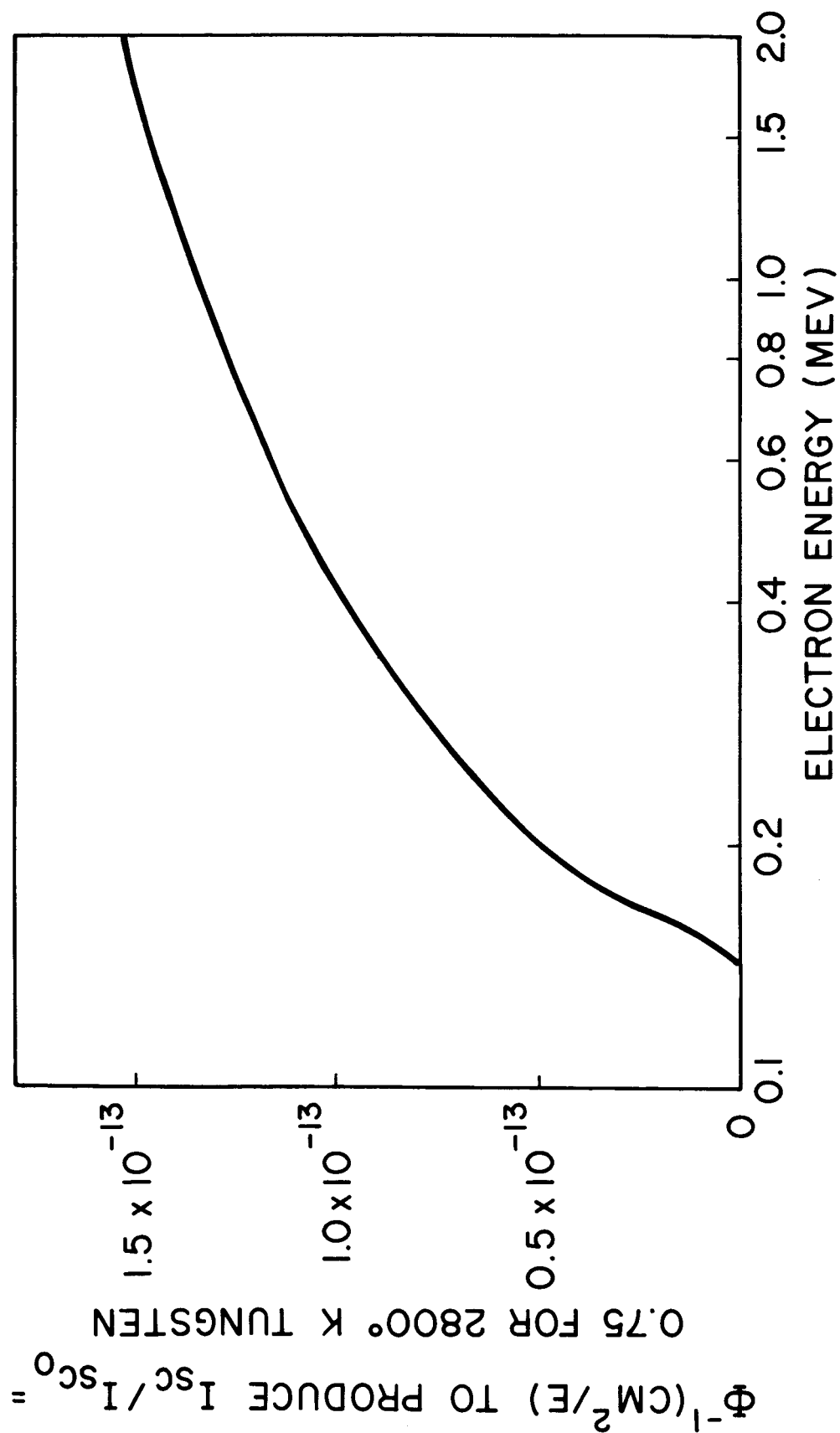


Figure 6. Energy Dependence of Silicon Solar Cell Short Circuit Current for Electron Bombardment

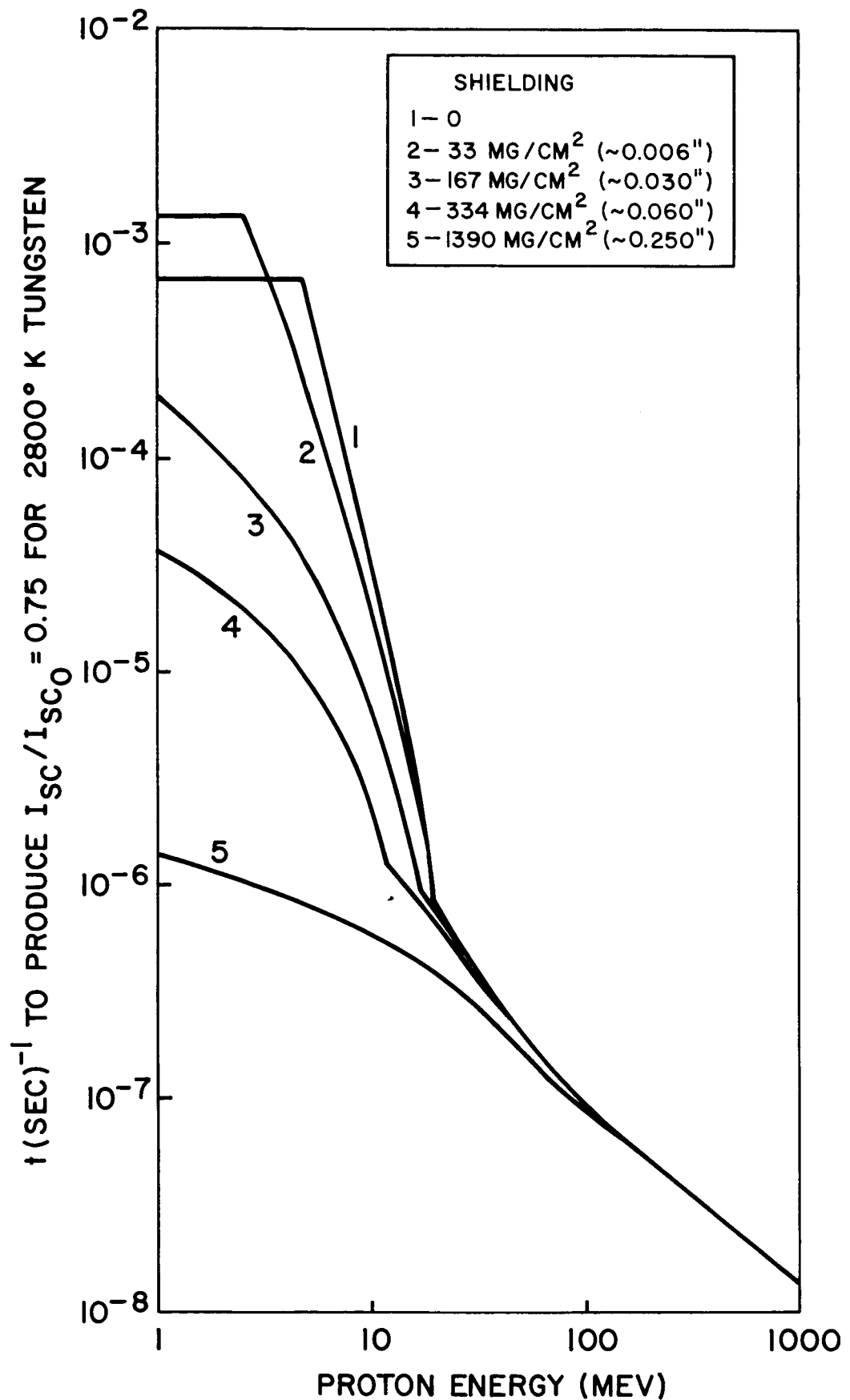


Figure 7. Effect of Thin Shields on the Inner Belt Proton Integral Spectrum in Terms of Time to Produce 25 Per Cent Degradation

are sensitive to the lower energy limit of the inner belt protons. We have terminated the proton distribution at 5 Mev, arbitrarily, in the absence of low energy data (curve 1, Figure 7). Thin shields (curve 2, Figure 7), depending upon the low energy limit, can increase the damage above that obtained with no shield. This effect results from the attenuation of the proton energy and the increased effectiveness of the lower energy protons. However, low energy protons probably exist below 5 Mev and the increase in damage with thin shields may not actually occur in spacecraft. As the shield thickness is increased, considerable improvement results because of the elimination of high intensity, low energy protons.

The effect of shielding on solar cells exposed in the outer belt is shown in Figure 8. Figure 8 was constructed in a manner similar to Figure 7; the differential electron intensity was multiplied by the damage cross section and integrated with respect to energy. The results are plotted as a function of the integral electron energy distribution. The low energy termination of the electron spectrum is unimportant because the damage results from electrons above 145 kev.

Figures 7 and 8 illustrate the importance of shielding in reducing radiation damage. The protection afforded by thin shields must be balanced against a number of factors, most of which are incompletely known at this time. For example, system considerations should include the additional weight of shielding compared to the addition of more cells with less shielding, the use of more efficient solar cells and the use of more radiation resistant cells, provided a sacrifice in efficiency does not occur. The damage resulting from exposure to protons and the choice of shielding depends strongly upon the population of low energy protons. The results shown in Figures 7 and 8 have been obtained using solar cell data from tungsten illumination. Solar illumination will change the ordinate on each figure by about a factor of three for most cells. This correction is dependent upon the spectral sensitivity of the particular cell.

#### V. SHIELDING, RADIATION RESISTANCE, AND CELL IMPROVEMENT

Exposure of solar cells continuously in the heart of the inner or outer Van Allen belt produces radiation damage rapidly; about one-half day in the inner belt and about 10 days in the outer belt degrades a typical cell 25 per cent (Figures 7 and 8, respectively, corrected to solar spectrum in order to avoid the obvious misinterpretation). Similar

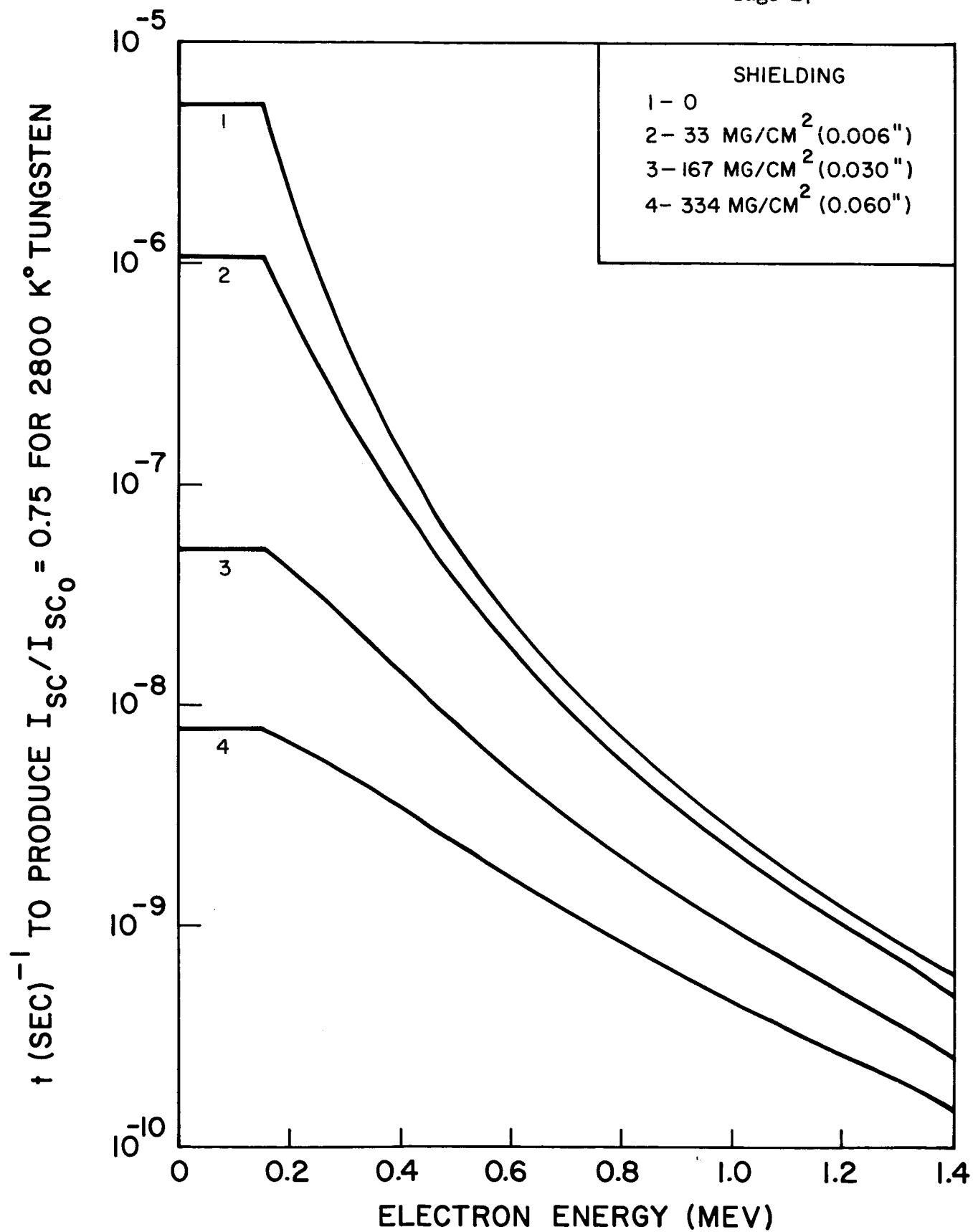


Figure 8. Effect of Thin Shields on the Outer Belt Electron Integral Spectrum in Terms of Time to Produce 25 Per Cent Degradation

effects can be expected from solar flare exposure, as well, but at an appropriately reduced rate. Most spacecraft orbits are not exclusively contained within the belts and operational lifetimes are correspondingly increased above the minimums above. Limited spacecraft evidence supports the estimates above: Explorer VI suffered a 25 per cent loss in about 10 days<sup>7</sup> and uncertain telemetry from Transit 2A showed a surprising loss of 50 per cent in a low altitude orbit in the first year<sup>8</sup>.

Shielding cells and radiation sensitive components can increase significantly their operational life. Electron protection, because of the clearcut low energy limit, provides a definite improvement (Figure 8). The degree of proton protection from shields depends strongly on the low energy proton population; and, in some cases (Figure 7), the use of thin shields may increase the damage. Obviously, no practical shielding can provide protection from protons above about 100 Mev. In many instances, it may be desirable to consider additional cells and power supply overdesign in preference to shielding because of the logarithmic relation between power loss and time and because shields thicker than .020 inch are heavier than the cells they protect.

Acquisition of radiation resistance at the expense of initial cell efficiency has not been discussed adequately. Since certain cell types, e.g., n on p silicon and GaAs, tend to have lower conversion efficiencies, the increased "per cent of initial" radiation resistance may represent no absolute improvement in performance over conventional cells.

Considerable improvement in solar cell conversion efficiency and radiation resistance is probable. A factor of 20 improvement in radiation resistance over older cell types with no loss of initial efficiency has occurred recently. Figure 9 shows a comparison of recent cell types exposed to 20 Mev protons. Shallow diffused p on n cells made from "oxygen-free" silicon are superior to any other cell type tested; in addition, the p on n cells have higher conversion efficiency than most n on p cells. However, it is doubtful for a number of reasons that the relative absence of oxygen is solely responsible for the improvement. (For example, the use of "oxygen-free" silicon seems to make n on p cells more radiation sensitive.) The comparisons in Figure 9 are not exhaustive; increased

<sup>7</sup>J. M. Denney, ARS Energy Conversion for Space Power, Progress in Astronautics and Rocketry, 3, 345, (1961)

<sup>8</sup>Private Communication, H. B. Riblet, APL, John Hopkins University (July, 1961)

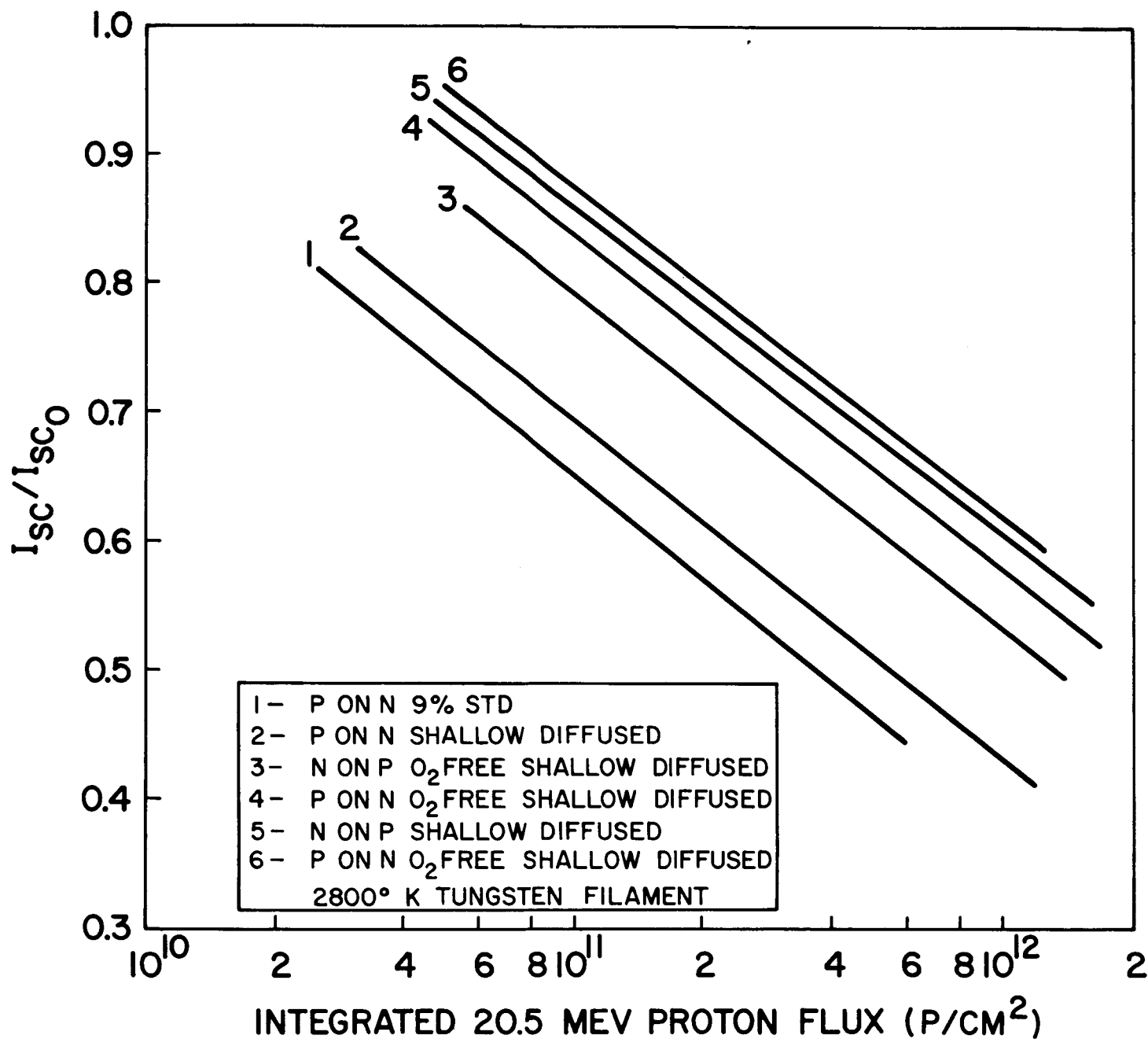


Figure 9. Effect of Oxygen Impurities on Silicon Solar Cell Degradation During 20 Mev Proton Bombardment



understanding of defect mechanisms in solar cells and the role of various impurities and imperfections can be expected to yield further improvement. Also, device design can significantly increase performance. In summary, radiation damage in solar cell power supplies will be a concern in many orbits, but cells with increased efficiency and radiation resistance can be anticipated.